Origins Theme Roadmap

David Black for the Origins Subcommittee
Breckenridge, Colorado
May 13, 1997

The Vision Statement

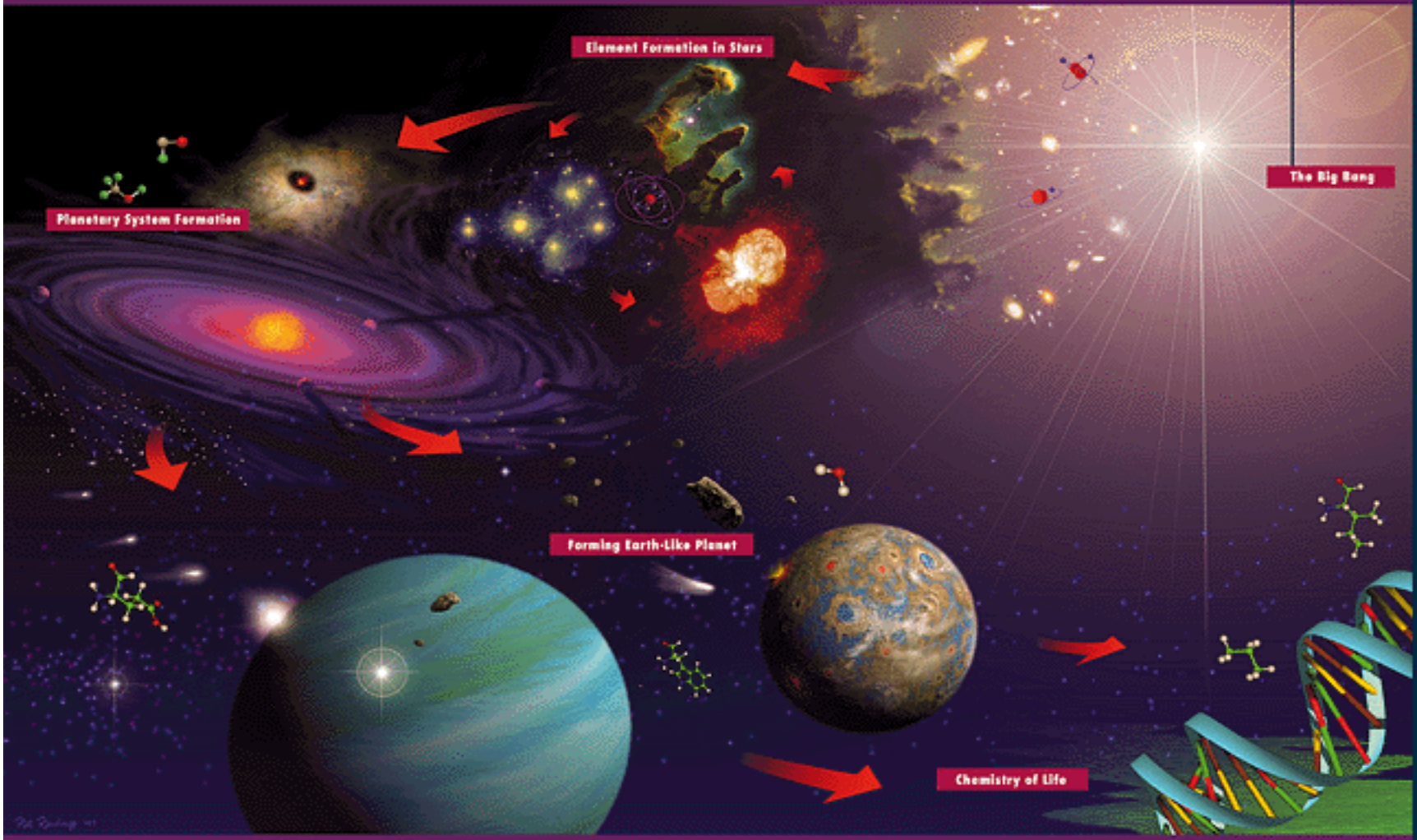
ORIGINS

"We seek to observe the creation of the earliest galaxies in the universe; to detect all planetary systems in the solar neighborhood and to find those planets that are capable of supporting life; and to demonstrate whether life began elsewhere in the solar system. We do this in order to understand and explain the origin of galaxies, stars and planetary systems, and life."

- Observations by COBE and by HST have yielded glimpses of the Universe bracketing that interval in the history of the Universe when galaxies formed, but the origin of galaxies lies where existing telescopes cannot reach.
- Observations by IRAS, Keck, various mm-wave observatories, and HST have provided a broad, but substantially incomplete, framework for understanding how stars and planetary systems form.
- Recent discoveries regarding life on Earth suggest a level of diversity and robustness for life that portend its presence on other planets in this and distant planetary systems.

These remarkable discoveries in diverse fields of scientific inquiry come to a focus in the Origins Program, a focus conceivable, but not realizable a decade ago.

ORIGINS



NASA's ORIGINS study follows the 15-billion-year-long chain of events from the birth of the Universe at the Big Bang, through the formation of the chemical elements, galaxies, stars, and planets, through the mixing of chemicals and energy that cradles life on Earth, to the earliest self-replicating organisms — and the profusion of life.

Roadmap Structure

ORIGINS

The framework used to define and convey the Origins Roadmap is hierarchical in nature:

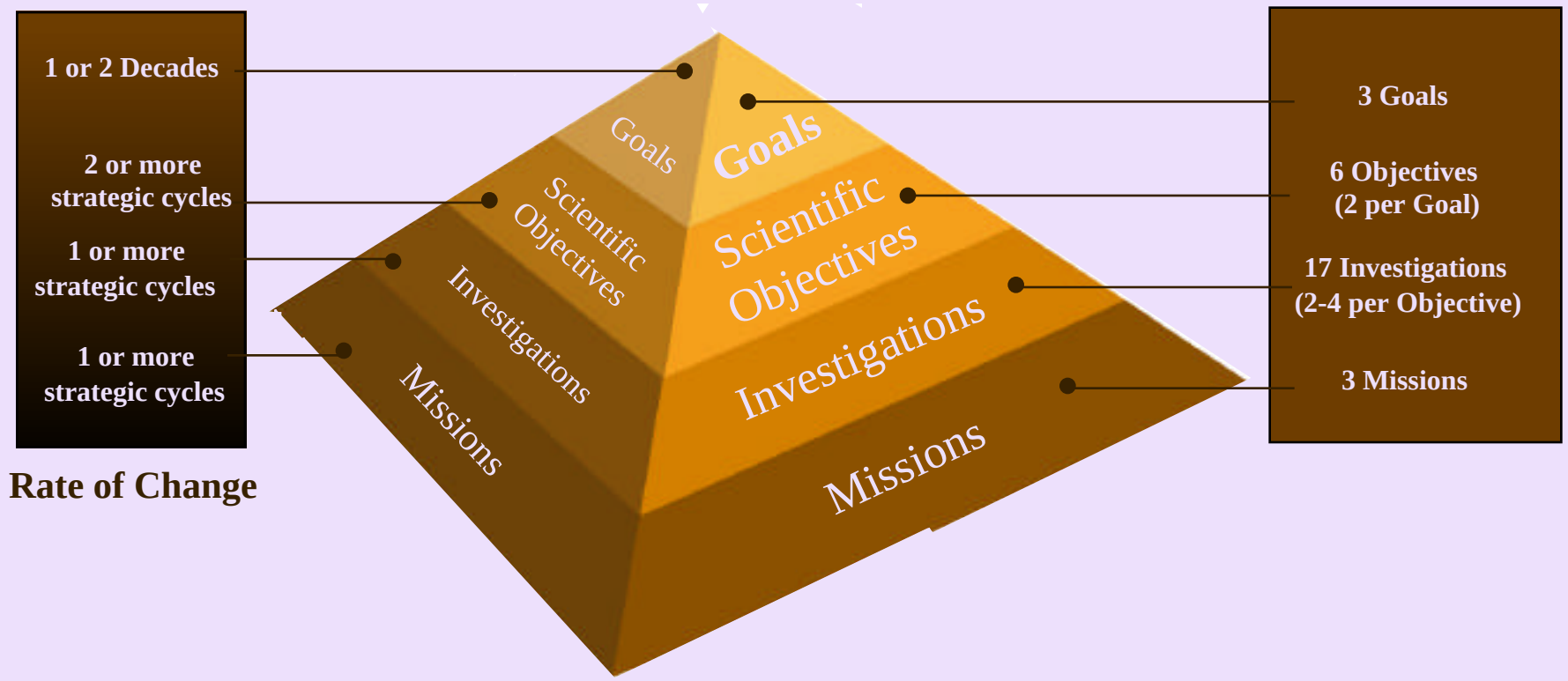
Scientific Goals (stable over decades)

Scientific Objectives (slowly changing from plan to plan)

Scientific Investigations (change from plan to plan)

Missions (flow from the Investigations)

Roadmap Structure



Galaxies --

Goal & Scientific Objectives

ORIGINS

Goal

- To ascertain how galaxies formed in the early universe and to understand the role of galaxies in the appearance of planetary system and life

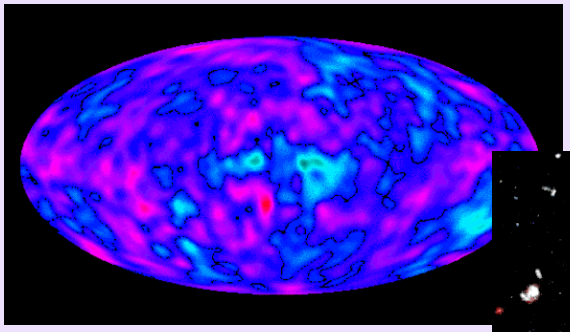
Scientific Objective 1

- What role did the gravity play in the emergence of galaxies from almost perfectly smooth particle sea of the early universe?

Scientific Objective 2

- Does the birth and the aging of a galaxy influence the chemical composition that is available to stars, and living organisms?

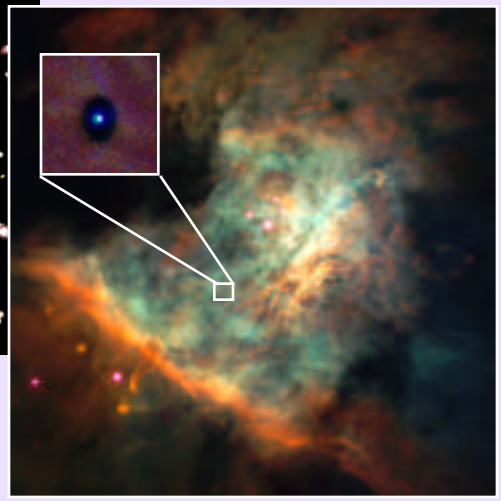
Galaxies -- A Critical Step to Life



Pre-galactic Universe

Early Galaxies

Potential Protoplanetary
Disk Around a Young Star



Galaxies --

Proposed Investigations

ORIGINS

Scientific Objective 1

What role did the gravity play in the emergence of galaxies from the almost perfect smooth particle sea of the early universe?

- **Investigations**

  (1) Determine the fate of baryonic matter as the Universe evolves

  (2) Measure the luminosities, forms, and environment of galaxies back to the epoch of their formation

Scientific Objective 2

Does the birth and the aging of a galaxy influence the chemical composition that is available to stars, and living organisms?

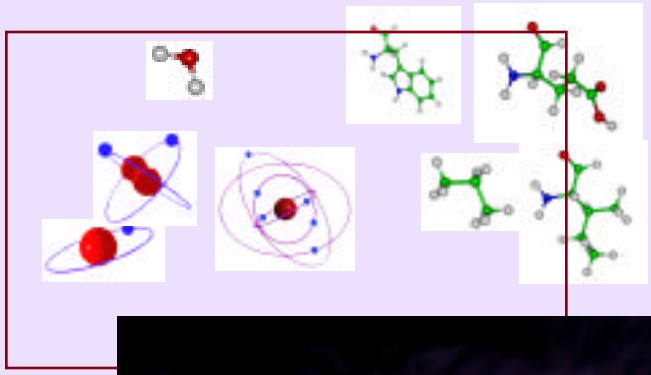
- **Investigations**

  (3) Trace the chemical evolution of the Universe from the birth of the first stars

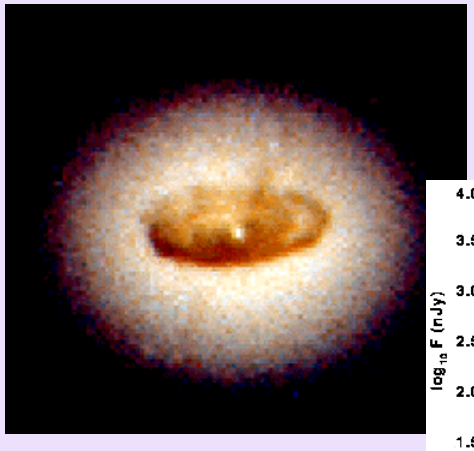
  (4) Follow the journey of the heavy chemical elements after their birth to the formation of dust, new generation of stars and planetary systems.

  (5) Determine when stars with planets capable of supporting life could have first appeared in the Universe.

Chemical Evolution: Galaxies, Stars and Planets

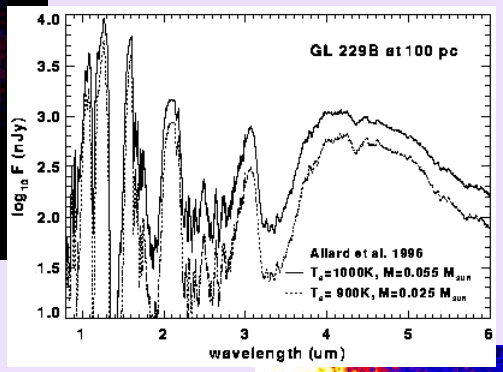


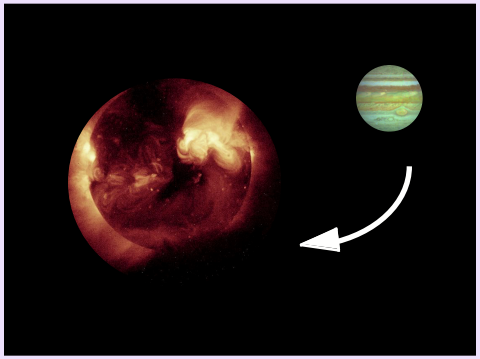
Evolution of Chemical Elements
and their Role in Generating
Stars and Planets



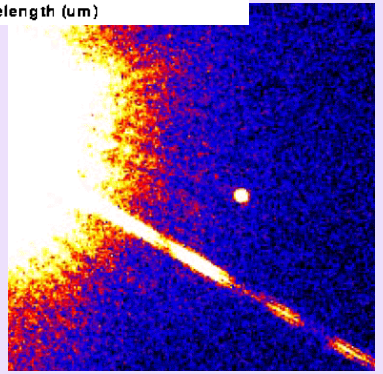
Black Holes

Fate of Baryonic Matter





Do Planets Capable of Supporting
Life form Around Metal Poor Stars?



Brown Dwarfs

Galaxies --

Elements of an Investigation -- an Example

ORIGINS

Investigation 2

- Measure the luminosities, forms, and environment of galaxies back to the epoch of their formation

  Key observations:

  Growth of galaxy structure, star formation rates, internal kinematics

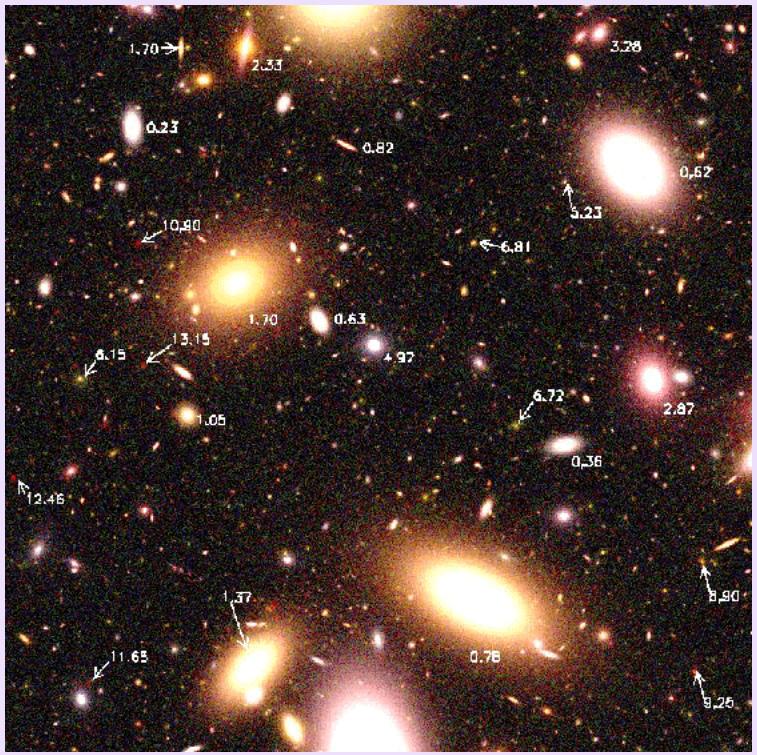
  Example:

  When did the first stars form?

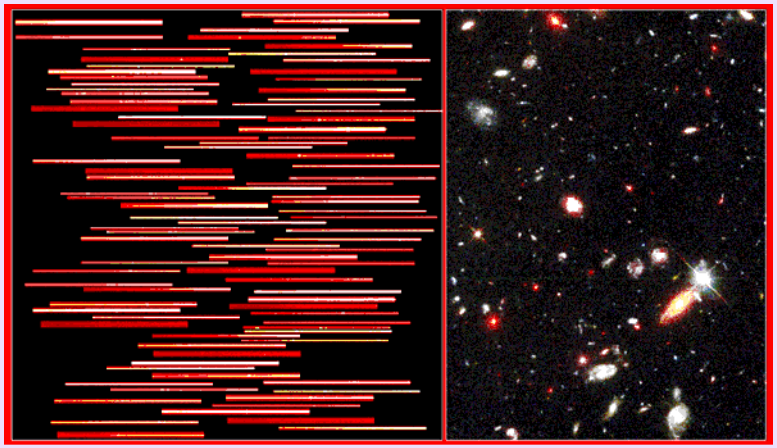
  Observations:

  - Deep multi-wavelength imaging visible to mid-IR to find the first star clusters $z > 5$
  - Synoptic, wide-field imaging to find $z > 5$ supernovae
  - Spectroscopy of selected examples to measure star formation rates, IMF, metal abundance, SN types and yield

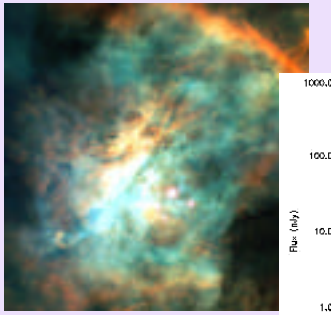
Trace Galaxies Back to Their Birth

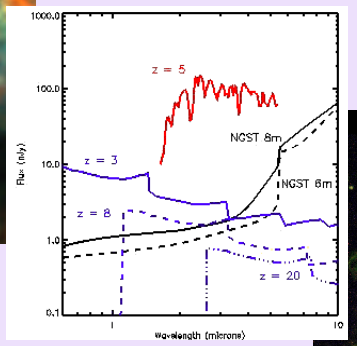


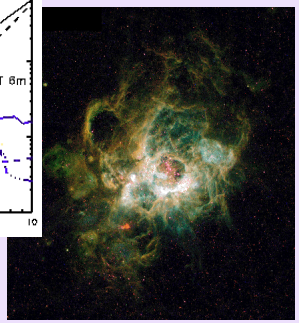
Formation of the First Galaxies



Deep Multi-Object Spectroscopy







The First Star Clusters and Supernovae (z>5)

Stellar and Planetary Systems --
Goals and Scientific Objectives

ORIGINS

Goal

- To understand how stars and planetary systems form and determine whether life-supporting planets exist around other stars

Scientific Objective 1

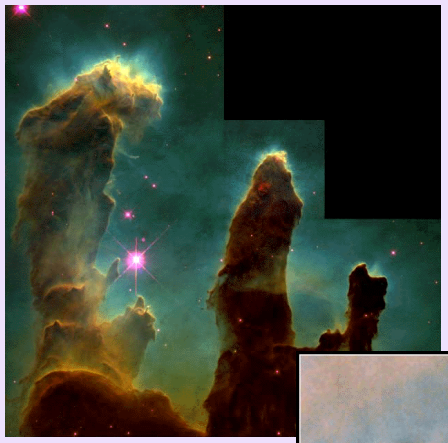
- Are planetary systems forming around other stars today?

Scientific Objective 2

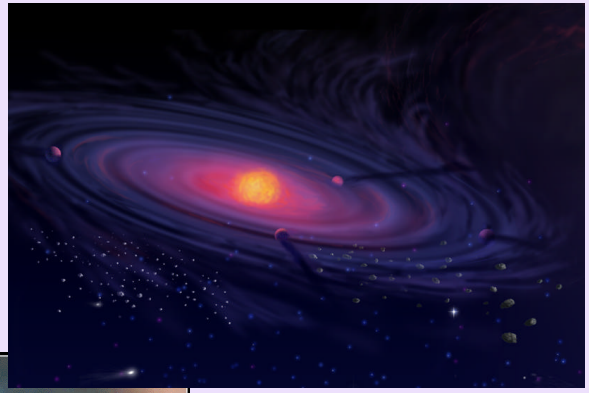
- Are there life-sustaining planets revolving around other stars in the solar neighborhood?

Birth and Evolution of Planetary Systems

Birth of Stars

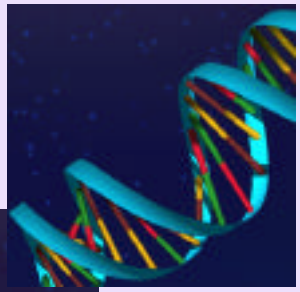


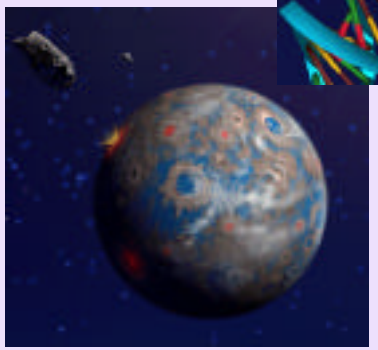
Evolving Protoplanetary Systems

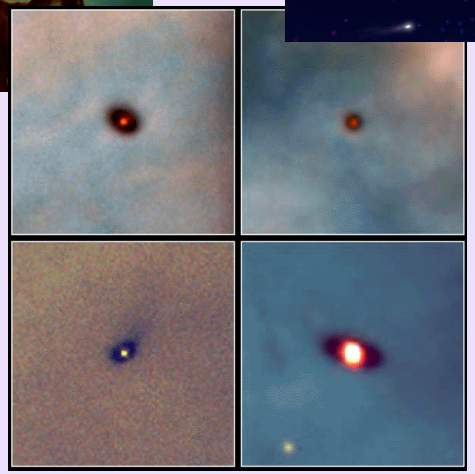


Search for Earth-like Planets

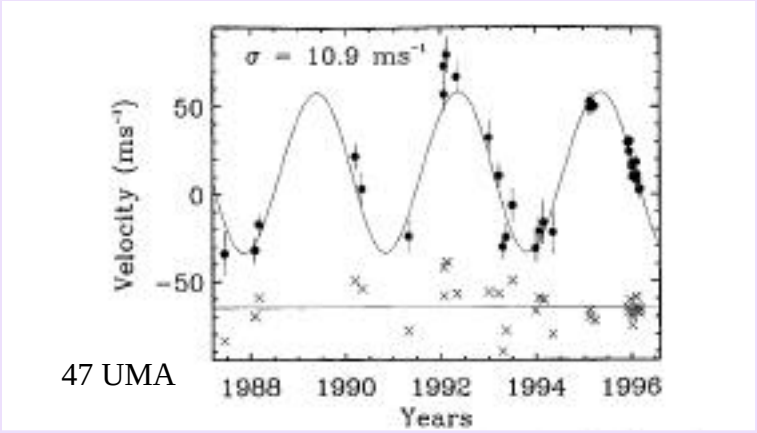
?







Protoplanetary Disk
Formation Around Young Stars



Ground-based Detection of
Jupiter-class Planets

Stellar and Planetary Systems --
Proposed Investigations

ORIGINS

Scientific Objective 1

Are planetary systems forming around other stars today?

Investigations

(1) Understand why molecular clouds produce mostly binary rather than single stars like the Sun

(2) Search for evidence of planet-forming disks around young stars

(3) Determine how planet-forming disks evolve

Scientific Objective 2

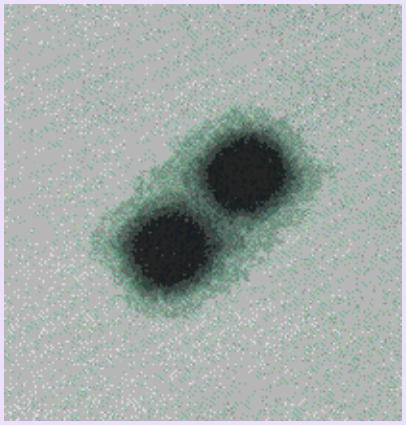
Are there life-sustaining planets revolving around other stars in the solar neighborhood?

Investigations

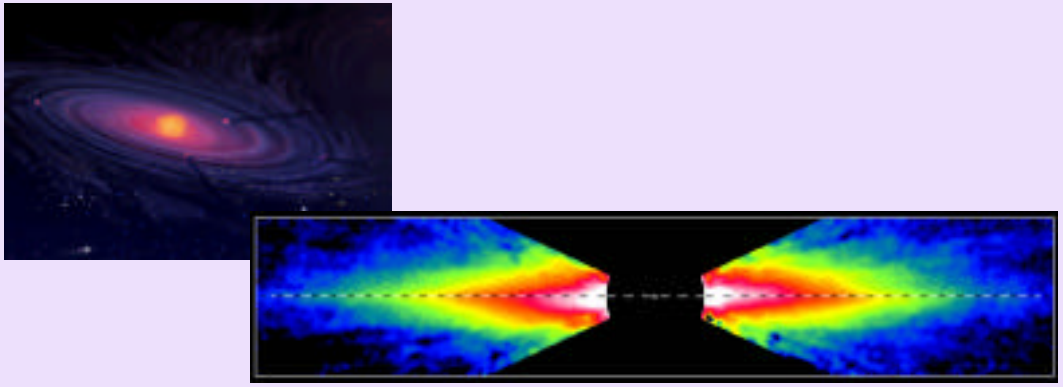
(4) Search for other planetary systems around a variety of stars and determine the orbits, masses and other properties of the planets

(5) Determine whether there are suitably temperate planets with atmospheres that might either support life or indicate the presence of life

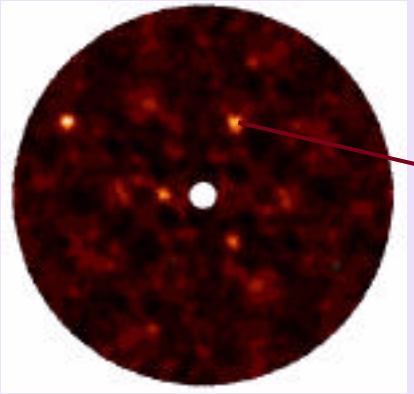
Stellar and Planetary Investigations



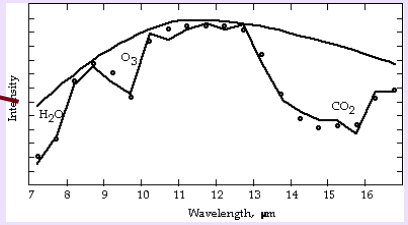
Binary Stars



Starlight Nulling to
Study Planet-forming Disks



Family Portrait
of Other Planetary Systems



Characterization of Planets
to Detect Habitability or
Biological Activities

Stellar and Planetary Systems --
Elements of an Investigation -- an Example

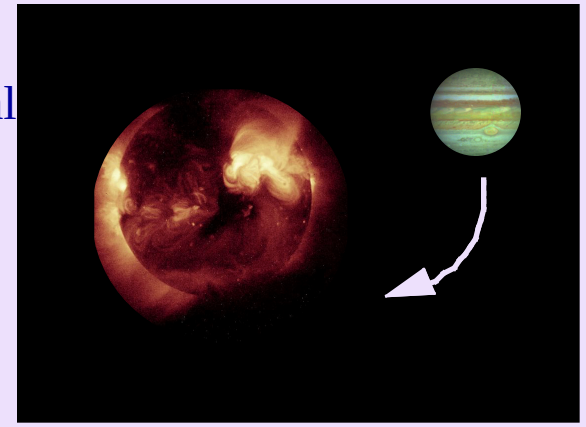
ORIGINS

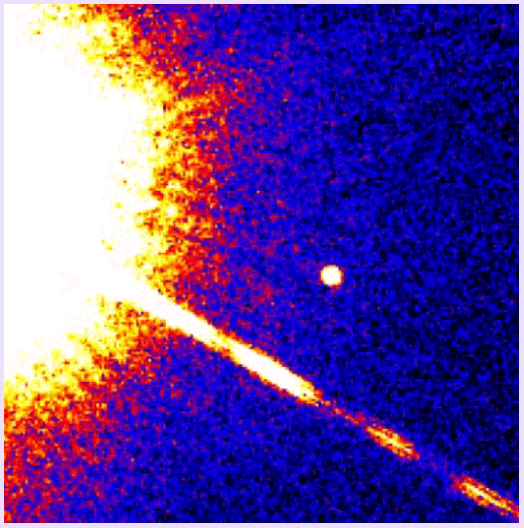
Investigation 4

- Search for other planetary systems around a variety of stars and determine the orbits, masses and other properties of the planets
  - Discoveries to date have been claimed to include brown dwarf stars, and Jovian-mass planets
  - Need statistics on giant planet properties, especially "normal" Jupiters with orbits that might permit existence of habitable Earth-like planets
  - Next step is to detect Uranus-mass planets, evidence for the core accretion model of giant planet formation
  - Ultimate goal is to detect Earth-mass planets orbiting in the habitable zones of their stars

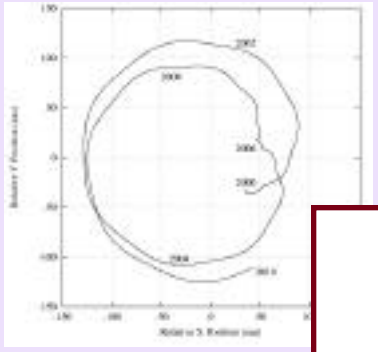
Search for Other Planetary Systems

Indirect Detection Based on Gravitational Pull of the Planet(s) on the Star

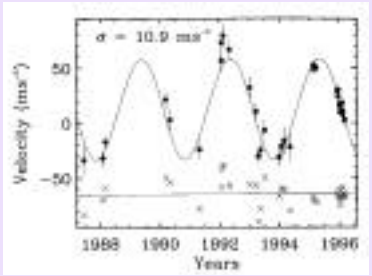




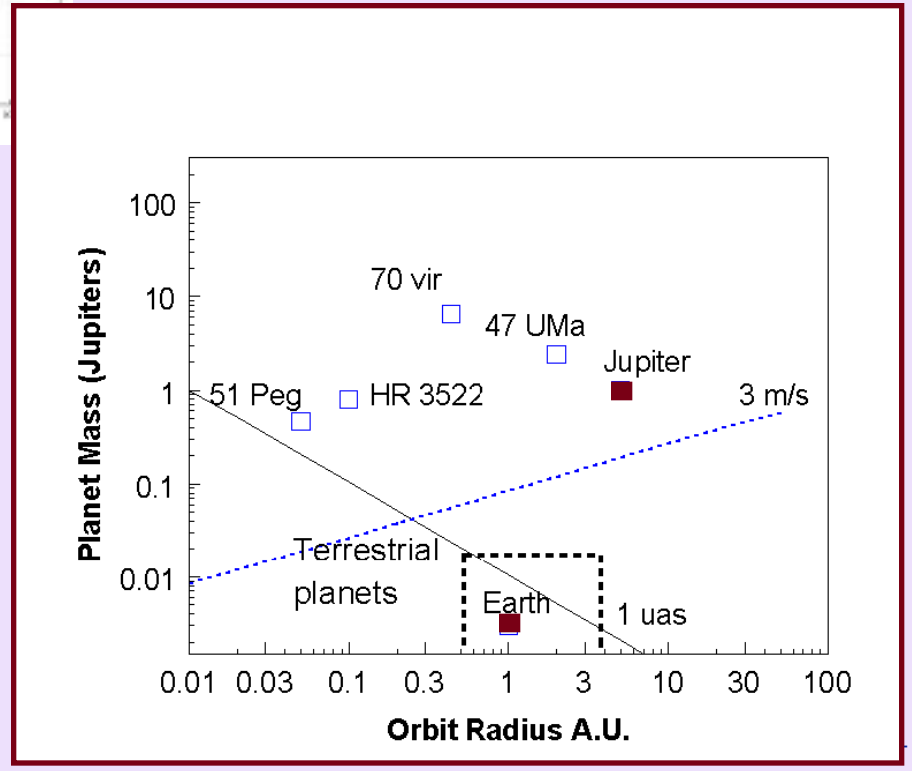
Current Direct Detection Limited to Very Large Companions -- Brown Dwarfs



Astrometric Signature



Radial Velocity Signature



Life --

Goals and Scientific Objectives

ORIGINS

Goal

- To understand how life originated on the Earth and to determine whether it began and may still exist elsewhere as well

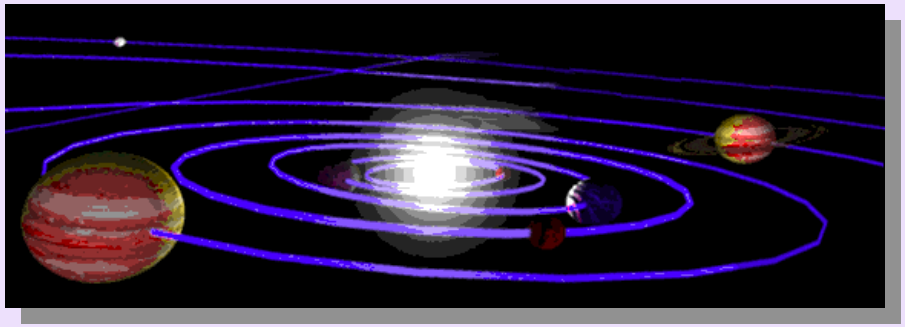
Scientific Objective 1

- Can a theory for the origin of life be developed from the knowledge of life on Earth?

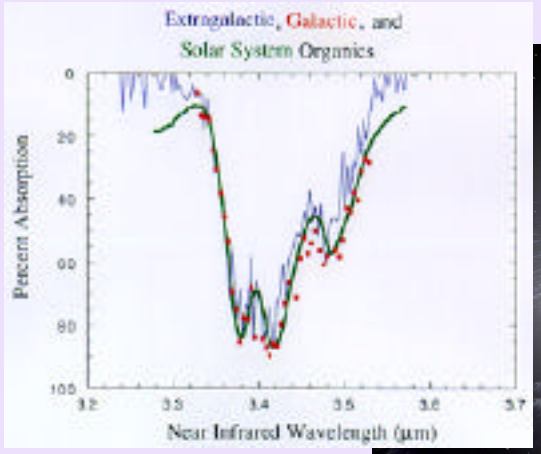
Scientific Objective 2

- Did life arise elsewhere in the Solar System and beyond. and does it exist there at the present time?

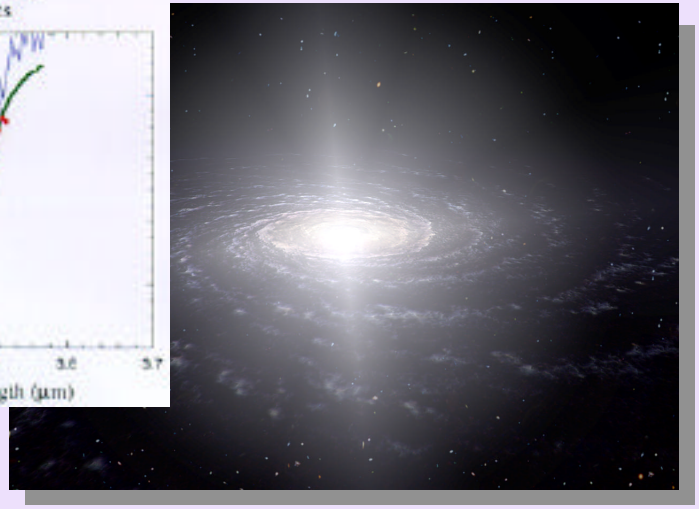
The Origin and Distribution of Life

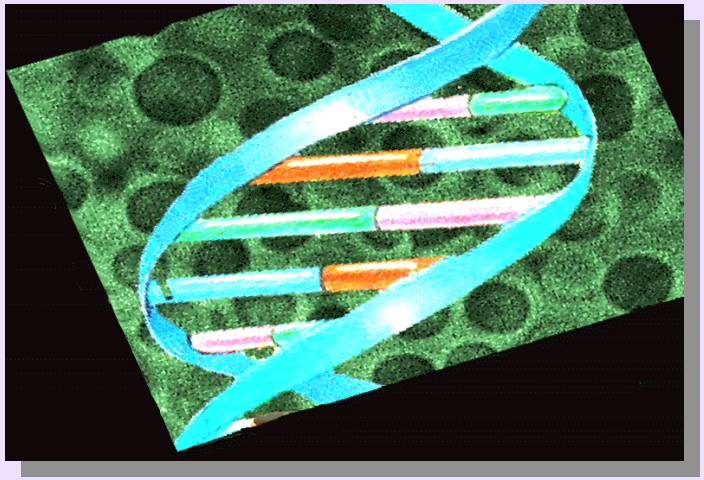


Other Biospheres?



Organic Matter
in the Cosmos





Origin of Life on Earth

Life --

Proposed Investigations

ORIGINS

Science Objective 1

Can a theory for the origin of life be developed from the knowledge of life on Earth?

Investigations

(1) Reconstruct the environmental history of the Earth in the first billion years when life arose

(2) Develop and test plausible pathways by which the ancient counterparts of membrane systems, proteins and nucleic acids formed from simple precursors and assembled into protocells

(3) Characterize the traits of the universal common ancestor through phylogenetic analyses of contemporary microorganisms

Science Objective 2

Did life arise elsewhere in the Solar System and beyond. and does it exist there at the present time?

Investigations

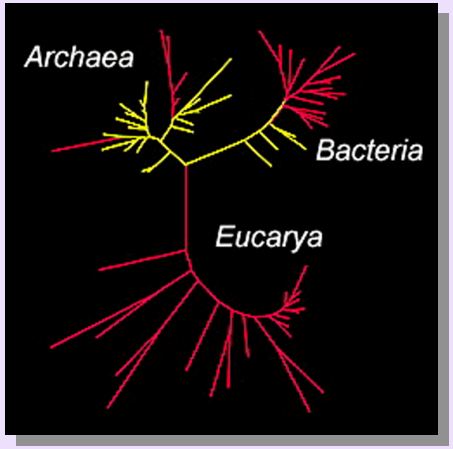
(4) Establish criteria to distinguish between materials of biological and non-biological origins in the Martian meteorite ALH84001 and other samples from Mars

(5) Determine the existence, morphology, biochemical characteristics and phylogeny of "nanobacteria" in extant microbial ecosystems

(6) Characterize the range of atmospheric compositions that might be produced by an anaerobic biosphere

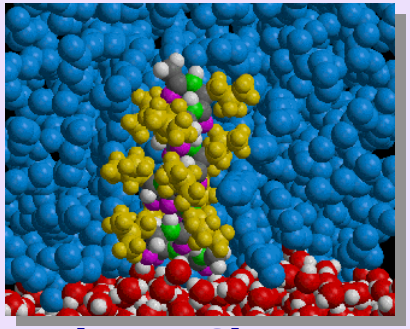
(7) Develop models for the compositional evolution of early Earth's atmosphere from initially anoxic to the accumulation of significant O_2

Life on Earth as a Paradigm for Life Elsewhere

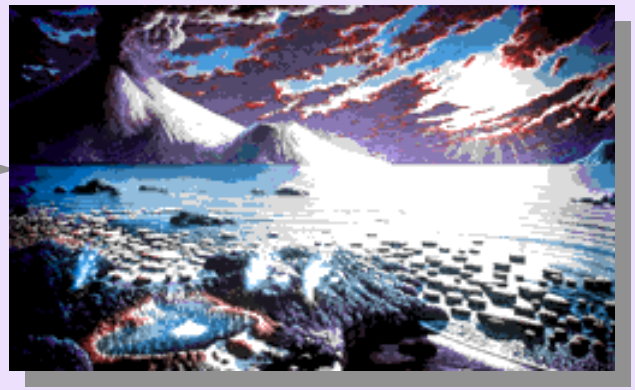


Biological Evolution

Origin of Life

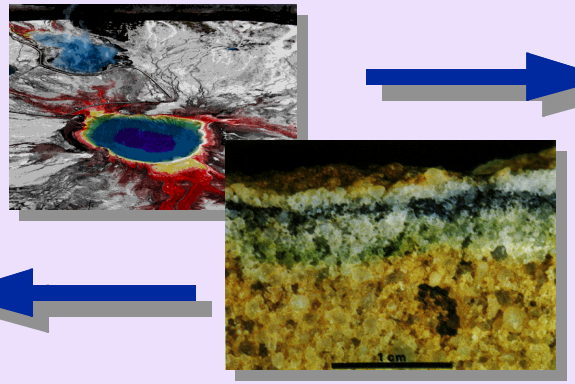


Prebiotic Chemistry

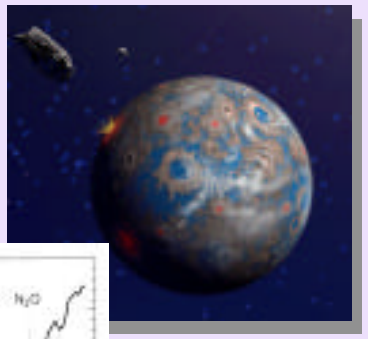


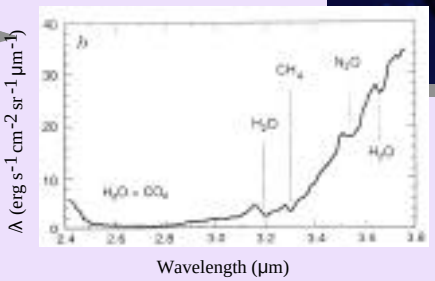
Earth's Earliest's Habitat

Past Life in Mars Meteorite?



Life in Extreme Environments





Signature of Anaerobic Biospheres

Life --

Elements of an Investigation -- an Example

ORIGINS

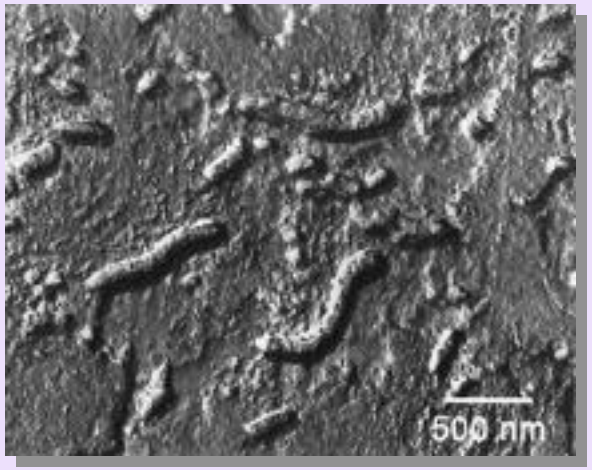
Investigation 4

- Establish criteria to distinguish between materials of biological and non-biological origins in Martian meteorite ALH84001 and other samples from Mars
  - Determine the mineralogical, chemical, isotopic, and morphological signatures of life produced in extreme environments
  - How well are these biomarkers preserved over time in the geological records?
  - Intensify the search for Martian meteorites in collaboration with NSF
  - Resolve the question of life in Martian meteorites in preparation for analysis of samples returned from Mars

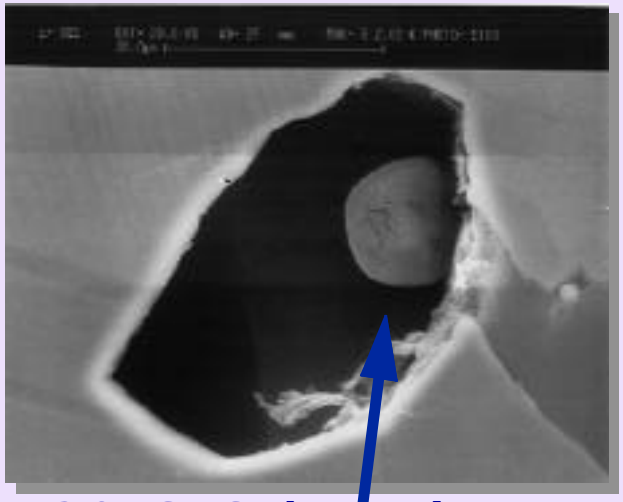
Establish Criteria for Biogenicity

3.5 Ga Stromatolite

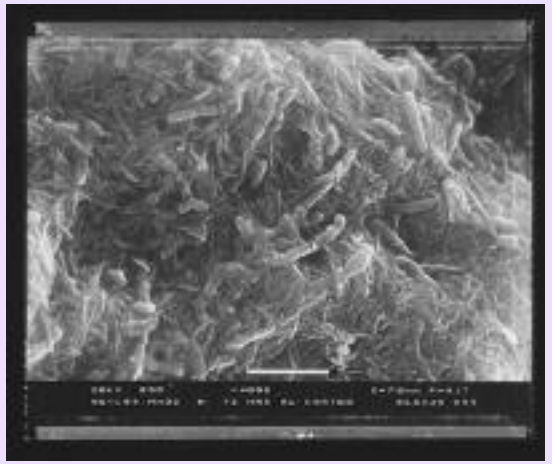
Nanofossils in ALH84001?



Preservation of Signatures Over Time



3.85 Ga Carbon Inclusion with Biogenic $^{13}C/^{12}C$



Microorganisms Colonizing Surface of MnO_2

Origins Mission Candidates

ORIGINS

- The mission candidates put forward in this Roadmap are of two general types: telescopes to be used primarily in studying objects outside the solar system, and robotic spacecraft to be used in studies of solar system objects. The latter requires close coordination with SSE theme, the former is further discussed here.

2000-2004 Time Frame

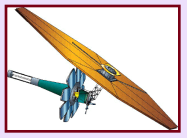
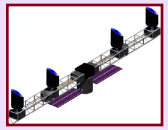
- We have identified 17 key Scientific Investigations, ten of which involve telescopic observations of objects ranging from high red shift galaxies to stars in the solar neighborhood. These telescopic investigations also involve measurements of unprecedented astrometric accuracy, as well as of high spectral and spatial resolution often of faint objects. Remarkably, two Mission Candidates address most of the key observational requirements: the **Space Interferometry Mission (SIM) and the Next Generation Space Telescope (NGST)**.

Longer Term Missions

- The highest priority long-term mission is the **Terrestrial Planet Finder (TPF)**. The TPF is currently envisioned as a long (several tens of meters) baseline infrared interferometer, operating in the wavelength range roughly from 7 - 20 μm. This region of the spectrum has been identified because it is an excellent region for the direct detection of terrestrial (i.e., small and rocky) planetary companions to other stars, as well as a region that is rich in molecular lines that could provide evidence as to the habitability of any planets that are discovered.

Missions/Investigations Overlay

● Significant Contributions
○ Contribution

(goal.objective.investigation)	SIM	NGST	TPF	R&A*
(1.1.1) Fate of baryonic matter		●		
(1.1.2) Early Galaxies		●		
(1.2.1) Chemical evolution of the Universe		●		
(1.2.2) Heavy chemical elements ⇒ planetary formation		●		
(1.2.3) First stars with planets capable of supporting life	●	○	●	
(2.1.1) Why mostly binary stars	●	○	○	
(2.1.2) Planet-forming disks around young stars	○	●	○	
(2.1.3) Evolution of planet- forming disks	●	●	○	
(2.2.1) Search for other planetary systems	●	○	●	
(2.2.2) Habitable or inhabited planets	○		●	
(3.1.1) Earth in the first billion years when life arose				●
(3.1.2) Prebiotic pathways -- molecules to protocells				●
(3.1.3) Traits of the universal common ancestor				●
(3.2.1) Criteria for biogenicity applicable to Mars samples				●
(3.2.2) “Nanobacteria” in extant microbial ecosystems				●
(3.2.3) Atmospheres produced by an anaerobic biospheres			○	●
(3.2.4) Models for early Earth atmosphere			○	●

*requires major enhancement of Origins R&A

Space Interferometry Mission (SIM)

An Origins Mission Candidate

ORIGINS

SIM will be the world's first long baseline optical interferometer in space opening up a whole new way of looking at the heavens

- Technological precursor to the Terrestrial Planet Finder (TPF) -- a cornerstone observatory in the Origins theme

- Its scientific advocacy dates back to the Bahcall Report (1990)
- Broad science applications with strong contribution to both Origins and SEU

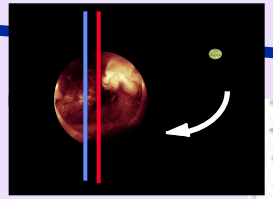
- Tremendous progress in the past several years toward the most challenging technologies
- A well-reviewed, fully funded technology plan will develop and test all critical H/W and S/W components well before NAR and PDR in 3/2001
- Detailed bottoms-up cost estimate reviewed by two independent teams

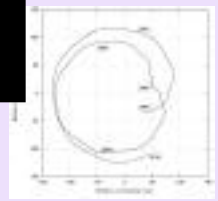
The Space Interferometry Mission (SIM)

Broad Science *and* Technological Precursor to Terrestrial Planet Finder

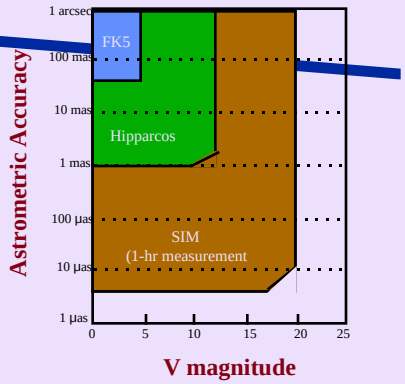
Technology

Science

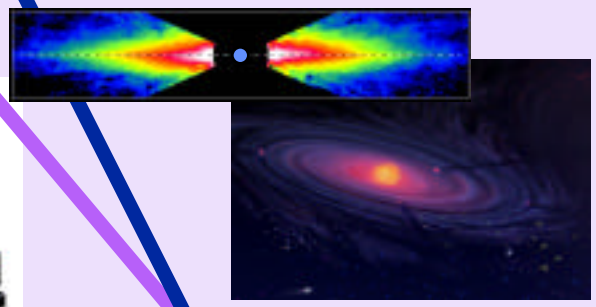




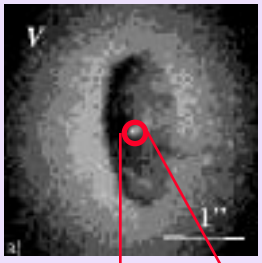
Indirect Detection of
Planets through Observation
of Thousands of Stars

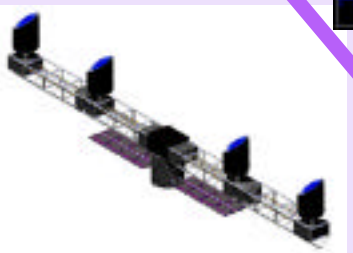


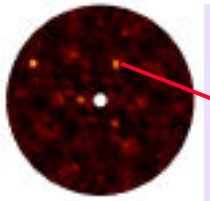
Age & Distances in the Universe
Orders of Magnitude
Improvement on Parallexes
in the Galaxy and Beyond



Nulling Imaging --
Structure of Planetary Disks



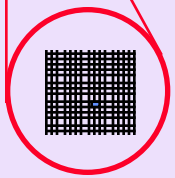




Planet Characterization

Family Portrait

10 milliarcsecond Imaging --
Dynamics & Evolution of AGNs



Next Generation Telescope (NGST)

An Origins Mission Candidate

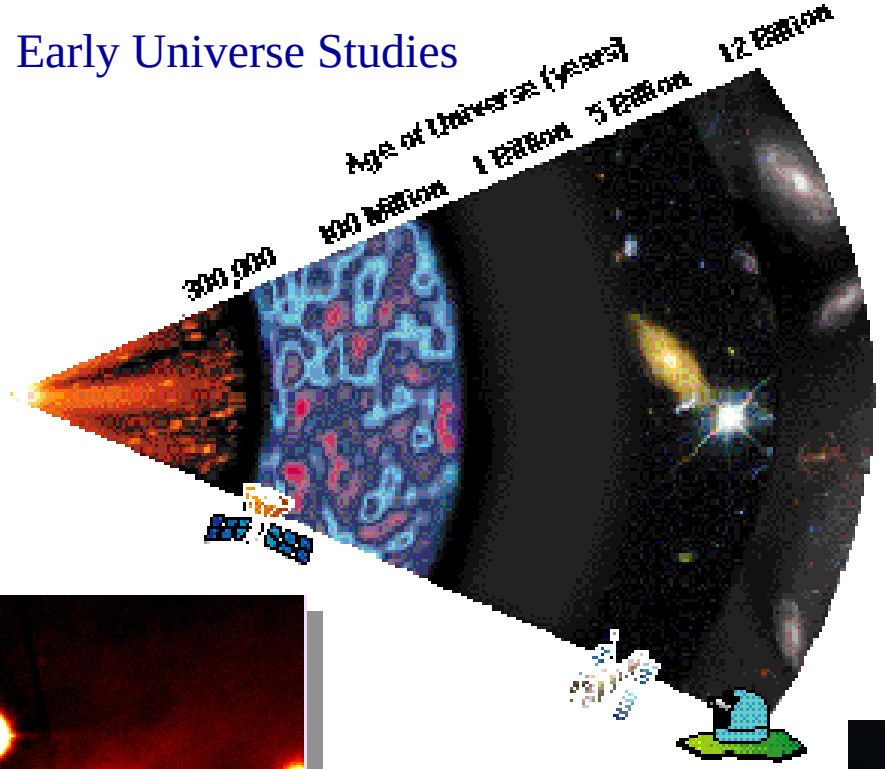
ORIGINS

- NGST will be the world's first large aperture space telescope which is passively cooled and background limited
  - Technological precursor to long-range Origins goals
- The NGST mission is a direct response to the science requirements put forth in the *HST and Beyond Report* (Dressler 1996)
- Broad science applications with strong contribution to both Origins and SEU and with contributions to SSE

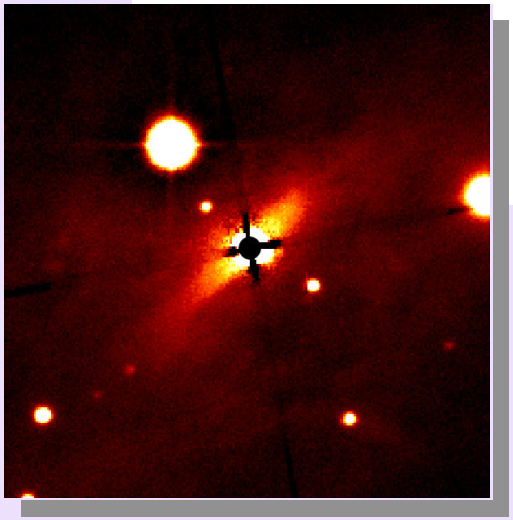
- Progress has been made on important enabling technologies:
  - Demonstrated a mirror with similar weight and accuracy requirements as NGST
  - Concepts using deployable primary have precursors in DoD
- A well-reviewed, technology plan will develop and test all critical H/W and S/W components prior to the beginning of Phase C/D in 2003
- Three study teams (TRW, Lockheed Martin, GSFC) determined that NGST could be constructed for $500M (FY96$)
  - Accurate costing of NGST remains high priority - two independent assessments underway

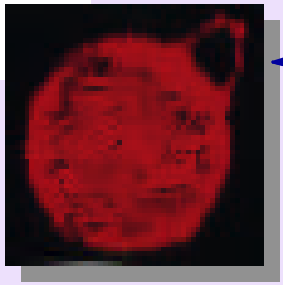
Next Generation Space Telescope

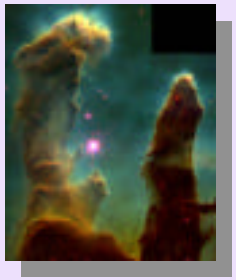
Early Universe Studies

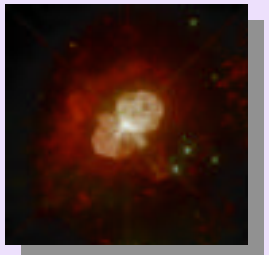


Creation of the Elements









Birth & Evolution of Planetary Systems

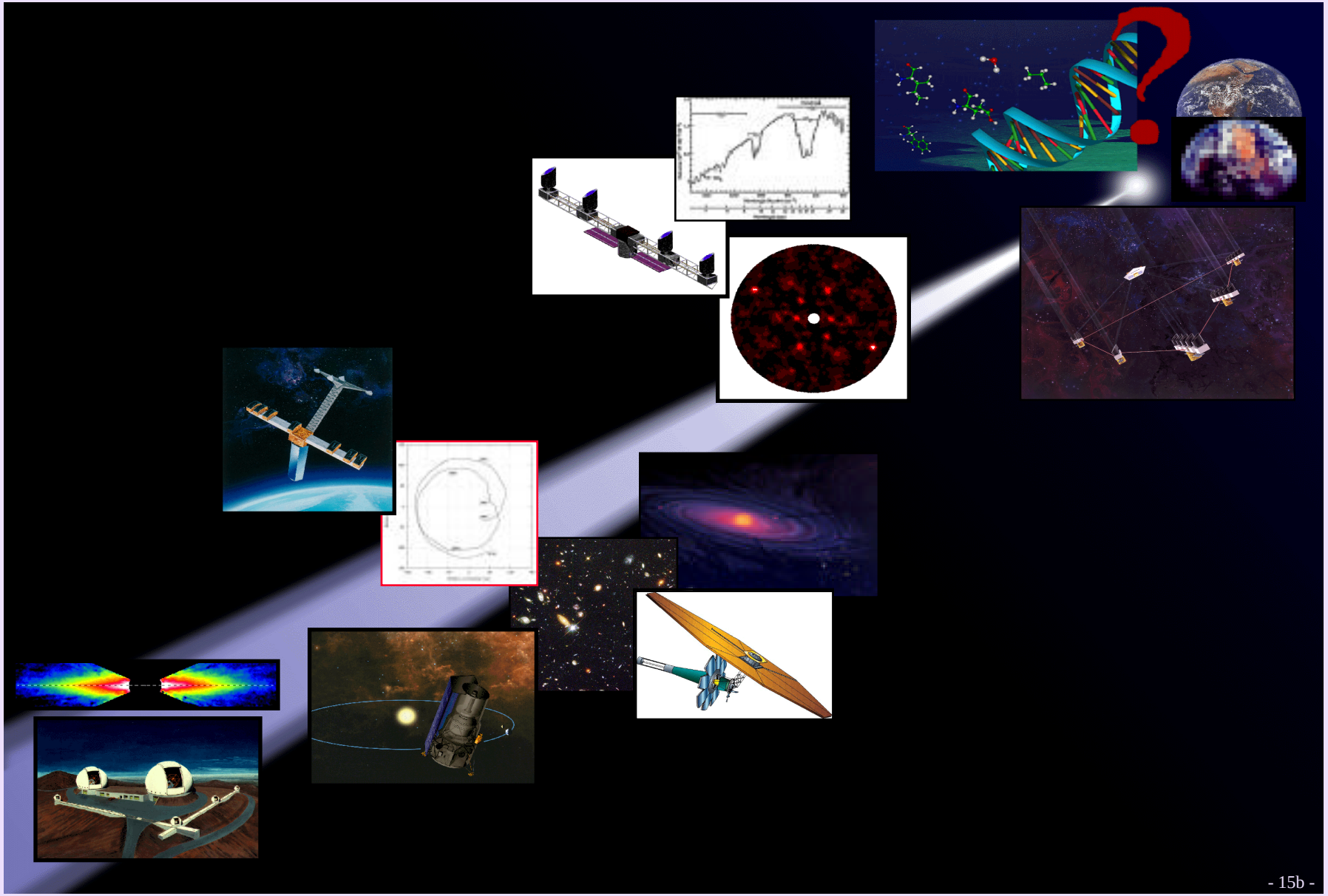
SIM and NGST

Major Steps in Progression of Discoveries

ORIGINS

- Before SIM and NGST, Origins will benefit from several space missions already in existence (HST) or currently in development phase (WIRE, SOFIA, FUSE) and ground observations
- Other space missions (SIRTF) and ground projects (e.g., KECK Interferometer) will contribute discoveries before launch of SIM and NGST
- And, after SIM and NGST, discoveries will continue with Terrestrial Planet Finder (TPF). Further over the horizon. a Terrestrial Planet Imager mission will further expand our views of planets like ours

Origins -- Progression of Discoveries



Alignment with National Civil Space Policy and Science Community Priorities

ORIGINS

From the President's New Civil Space Policy

1- "a Sustained program to support a robotics presence on the surface of Mars by the year 2000 for the purpose of scientific research, exploration and technology development"

2- " a long-term program, using innovative technologies, to obtain in-situ measurements and sample returns from the celestial bodies in solar system"

3- "a long-term program to identify and characterize planetary bodies in orbit around other stars"

From Report of Task Group on Space Astronomy and Astrophysics

In ranked order the recommended priorities are as follows:

1- Determination of the geometry and content of the Universe by measurement of the fine-scale anisotopy of the cosmic background radiation;

2- Investigation of galaxies near the time of their formation at very high redshift;

3- Detection and study of planets around nearby stars; and

4- Measurement of the properties of black holes of all sizes

The second and third priorities are given virtually the same weight

Origins:

Galaxies, Stars, Planets
and ...Life